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Abstract - We demonstrate the formation of highly resistive single-crystal ZnO epilayers as a result of irradiation with MeV Li, O, and Si ions. Results show that the ion doses necessary for electrical isolation close-to-inversely depend on the number of ion-beam-generated atomic displacements. However, in all the cases studied, defect-induced electrical isolation of ZnO is unstable to rapid thermal annealing at temperatures above about 300 °C. No significant improvement of thermal stability is found by varying ion mass, dose, and irradiation temperature (up to 350 °C). Finally, a comparison of implant isolation in ZnO with that in GaN is presented.

A. Introduction

Single-crystal ZnO has recently received significant interest due to important potential applications of this material in the fabrication of (opto)electronic devices (see, for example, [1,2]). The main practical advantages of ZnO include a direct band-gap (~ 3.4 eV at room temperature), a bulk growth capability, amenability to conventional chemical wet etching, convenient cleavage planes, and a large excitonic binding energy (60 meV) [1,2]. This makes ZnO an ideal candidate for (opto)electronic device applications. However, in addition to desired fundamental properties, the fabrication of ZnO-based (opto)electronic devices obviously requires development of a device processing technology. At present, there are significant challenges for processing ZnO including electrical isolation. Such electrical isolation can be achieved by ion implantation where the material is rendered highly resistive by the ion beam under appropriate conditions (see, for example, [3]). It is generally believed that irradiation-induced degradation of carrier mobility as well as the trapping of carriers at deep centers associated with irradiation-produced damage (defect isolation) or with implanted species (chemical isolation) is the mechanism responsible for electrical isolation of semiconductors [3].

Although electrical properties of single-crystal ZnO bombarded with electrons or light ions have previously been studied [4-7], we are not aware of any reports demonstrating that ZnO can be rendered highly resistive, as required for electrical isolation. In this paper, we demonstrate irradiation-induced formation of highly resistive layers in *n*-type single-crystal ZnO epilayers. We have also investigated thermal stability of electrical isolation in ZnO.

Table I. Implant conditions used in this study.

Ion	Energy (MeV)	Implantation temperature (°C)	Beam flux (10^{11} cm^{-2} s^{-1})
^{7}Li	0.7	20	1.9
^{16}O	2.0	20, 350	1.9
^{28}Si	3.5	20	1.0

B. Experimental

The n-type single-crystal wurtzite ZnO epilayers used in this study were ~ 0.6 μm thick, epitaxially grown on a-plane sapphire substrates by molecular beam epitaxy at OIT. A further description of growth conditions can be found elsewhere [8]. As-grown epilayers had a room-temperature free electron concentration of ~ 10^{17} cm^{-3}, an effective Hall mobility of ~ 80 cm^2 V^{-1} s^{-1}, and a sheet resistance of ~ 1 kΩ/sq. Resistors of ~ 3.5×3.5~mm^2 in size were prepared with In-Ga eutectic Ohmic contacts on two opposite sides of each sample. These ZnO resistors were bombarded in an ANU 1.7 MV tandem accelerator (NEC, 5SDH-4) under ion irradiation conditions given in Table I. Ion energies were chosen to place the damage peak deep into the sapphire substrate, beyond the ZnO layer. During ion bombardment, samples were tilted by ~ 7° off the surface normal direction to minimize channeling. Sheet resistance (R_s) was measured *in-situ* after each dose step using a Keithley 619 electrometer. Postirradiation isochronal annealing was carried out in a rapid thermal annealing (RTA) system for 60 s in an Ar ambient at atmospheric pressure.

C. Results and discussion

C.1 Creation of highly resistive ZnO

Figure 1(a) shows the evolution of R_s of ZnO resistors irradiated with Li, O, and Si ions, illustrating that, similar to the situation for other semiconductors [3,9,10], R_s increases as a result of ion irradiation. In all the samples studied, the values of R_s reach the maximum after some characteristic dose (the so called threshold isolation dose [9,10] – Φ_{th}). The levels of R_s at the plateaus shown in Fig. 1(a) for doses above Φ_{th} are ~ 4×10^{10} Ω/sq. However, it should be noted that the real maximum values of R_s can be even larger because the R_s values measured have a contribution from the parasitic resistances of the experimental set-up, which are of the same order of magnitude.

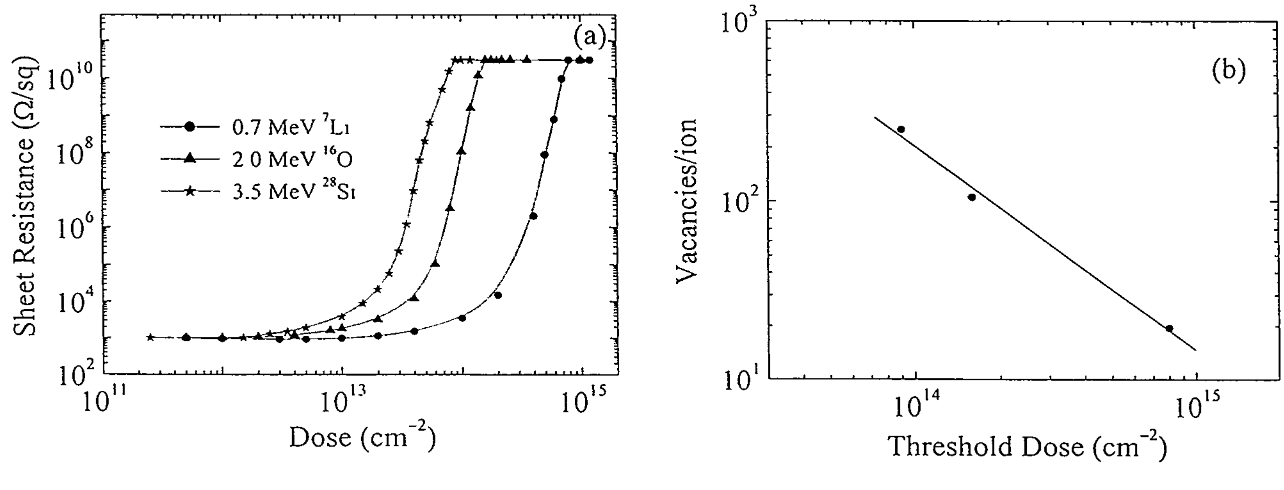

Fig. 1. (a) Dose dependence of R_s of ZnO bombarded with different ions, as indicated in the legend. (b) Average number of ion-beam-generated lattice vacancies within the 0.6-μm-thick ZnO epilayer is plotted vs threshold ion doses Φ_{th}. Also shown is a straight line with a slope of -1.14±0.10, which represents the best fit to the Φ_{th} dependence. See Table I for the details of implant conditions.

Figure 1(a) also shows that the isolation curves progressively shift toward lower doses with increasing ion mass. Such a shift is caused by an increase in the number of ion-beam-generated atomic displacements with increasing ion mass. This ion mass effect is better illustrated in Fig. 1(b), showing the average number of lattice vacancies produced by different ions within ZnO epilayers vs Φ_{th}. A straight line fit with a slope of -1.14 ± 0.10 represents the best fit to the Φ_{th} dependence. Thus, results from Fig. 1(b) indicate that the efficiency of the carrier removal process close-to-inversely depends on the number of ion-beam-generated atomic displacements.

C.2 Thermal stability

Figure 2(a) shows the evolution of R_s as a function of temperature of isochronal annealing of ZnO epilayers bombarded with Li, O, and Si ions. Note that all these cases, ion doses are above Φ_{th}, as can be seen from Fig. 1(a). It is clearly seen from Fig. 2(a) that, in all the cases studied, defect-induced electrical isolation of ZnO is unstable to RTA at temperatures above ~ 300 °C, and R_s is recovered to close to its original value after annealing at ~ 650 °C. It is also seen from Fig. 2(a) that the thermal stability of electrical isolation is different for different ion species and doses, consistent with previous studies of electrical isolation in other compound semiconductors (see, for example, [11]). In addition, Fig. 2(b) illustrates thermal stability of electrical isolation in ZnO bombarded with 2 MeV O ions to different doses (above Φ_{th}). Figure 2(b) reveals an insignificant increase in thermal stability with increasing ion dose up to ~ 2 orders of magnitude above Φ_{th}. Our results also show that elevated temperature irradiation (with 2 MeV O ions at temperatures up to 350 °C) does not improve the thermal stability of isolation. Hence, at present, more work is needed to improve the thermal stability of electrical isolation in ZnO.

C.3 Comparison with GaN

It is interesting to make a comparison of results of the present study with isolation data for another wide band-gap semiconductor, GaN, studied in detail previously (see, for example, [9,10] and references therein). First of all, a comparison of Fig. 1 with previous

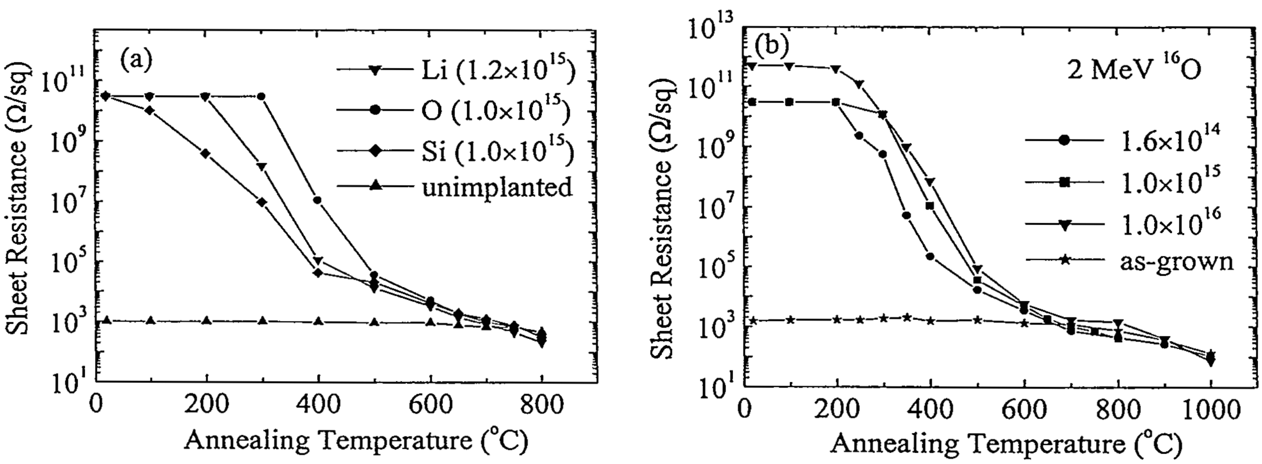

Fig. 2. (a) Evolution of R_s as a function of temperature of isochronal annealing of ZnO epilayers bombarded with different ions to different doses (in cm^{-2}), as indicated in the legend. See Table I for the details of implant conditions. The evolution of sheet resistance of an as-grown (unirradiated) sample during annealing is also shown for comparison. (b) The same as (a) but for the case of irradiation with 2 MeV O ions to different doses.

isolation data [9,10] shows that the ion doses (and, hence, the number of ion-beam-generated atomic displacements) needed to isolate ZnO are ~ 2 orders of magnitude larger than isolation doses in the case of GaN. This is a direct consequence of extremely efficient dynamic annealing of ion-beam-generated point defects in ZnO (i.e., migration and interaction of defects *during* ion irradiation), as has been studied in a number of previous reports [4,6,7,12-14]. Due to a large mobility of Frenkel pairs in ZnO, most of ion-beam-generated point defects experience annihilation, and only a small portion of defects survives annihilation and forms stable defect complexes.

D. Concluding remarks

In conclusion, we have demonstrated that sheet resistance of ZnO epilayers can be increased by ~ 7–8 orders of magnitude as a result of irradiation with MeV light ions. Results have shown that the ion doses necessary for electrical isolation inversely depend on the number of lattice displacements produced by the ion beam. However, such defect-induced electrical isolation of ZnO is thermally stable only for temperatures up to ~ 300 °C, and R_s can be completely recovered to close to its original value by annealing at ~ 650 °C.

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